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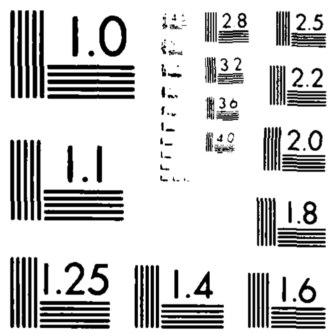

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Status and Prospects of Computational Fluid Dynamics for Unsteady Transonic Viscous Flows

W.J. McCroskey, P. Kutler, and J.O. Bridgeman

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SUMMARY

Applications of computational aerodynamics to aeronautical research, design, and analysis have increased rapidly over the past decade, and these applications offer significant benefits to aeroelasticians. This paper traces the past developments by means of a number of specific examples, and projects the trends over the next several years. The crucial factors that limit the present capabilities for unsteady analyses are identified; they include computer speed and memory, algorithm and solution methods, grid generation, turbulence modeling, vortex modeling, data processing, and coupling of the aerodynamic and structural dynamic analyses. The prospects for overcoming these limitations are presented, and many improvements appear to be readily attainable. If so, a complete and reliable numerical simulation of the unsteady, transonic viscous flow around a realistic fighter aircraft configuration could become possible within the next decade. The possibilities of using artificial intelligence concepts to hasten the achievement of this goal are also discussed.

1. INTRODUCTION

The extraordinary growth in computer technology of the past two decades has revolutionized the design of modern aircraft, especially aircraft that cruise or maneuver in the transonic flow regime. There is no need to belabor the contributions of computational fluid dynamics (CFD) to solving aeronautical problems, as a large number of review papers have been written on this subject; Refs. 1-7 are but a small sample. Suffice it to say that the requirements and potential benefits for predicting the performance and steady airloads of advanced aircraft have been a major driving force in the development of existing CFD technology and contemporary supercomputers; and that, as a result, impressive capabilities exist today. This paper addresses the current status and the prospects for developing new CFD methodology to predict the aeroelastic behavior of future advanced aircraft. We will focus on the principal factors that will determine the success or failure of computational aerodynamics to meet the needs of aeroelasticians, and on the future developments that might be expected to alter these factors.

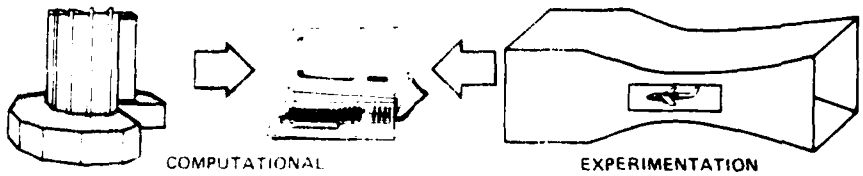
The demands of the aeroelasticity community on aerodynamicists are staggering. For dozens or even hundreds of cases, they are asked to provide the three-dimensional, unsteady airloads on complex geometries (including external stores) at transonic flight conditions for which viscous effects are important, and to couple these aerodynamic characteristics with the complex structural-dynamic behavior of the airframe. Furthermore, these results are to be obtained quickly, and without significantly increasing the national debt. Thus, calculating the flutter boundaries of flexible aircraft flying at transonic speeds is at least an order of magnitude more difficult than the more widely publicized task of predicting the performance of aerodynamic configurations in steady flight. Finally, aeroelastic calculations are more specialized, and fewer people are working in this area, than in steady *aerodynamics*. Fortunately, there is clear evidence in the 16 papers of this Specialists' Meeting, and elsewhere, that considerable progress has been and is being made toward adapting and extending the latest CFD methodology for steady flows into the unsteady domain. However, we will demonstrate that new thrusts, new ideas, and new levels of effort will be required to meet the aeroelasticians' future requirements.

One way to view the task of determining flutter behavior is to think of it as an exercise in simulation. That is, we want to avoid unacceptable catastrophes in real life by analyzing appropriate risk-free simulations of the phenomena. One may note, in passing, that this concept is more akin to the issues facing the nuclear power industry than to those of predicting aircraft performance. The point is that we wish to simulate a complex dynamics problem in solid mechanics which is driven by complicated, boundary-dependent, and nonlinear aerodynamic forcing functions. We now have available to us highly developed techniques for physical simulations (which we call wind-tunnel testing) and rapidly developing techniques for numerical simulation (which can combine large scientific computers, structural-dynamic analyses, and computational aerodynamics). Each type of simulation has its strengths and its limitations, as indicated in Fig. 1. The relative merits are frequently debated; but we shall not dwell on these issues here, except to argue for the judicious use <u>both</u> of experiment and computation to complement each other.

As discussed in Section 3, our projection is that complete and reliable numerical simulations will become possible within the next decade for complex configurations, and that high-quality physical experiments will play crucial roles in developing and validating these numerical simulations. However, the cost of the complete simulations may well be excessive for the hundreds of combinations of flow parameters, structural frequencies and mode shapes, and wing-store configurations that aeroelasticians will probably want to analyze. Therefore, there will clearly be an ongoing need for less costly, more approximate simulation methods, even though some accuracy may be sacrificed. The development and validation of such engineering simulations will be greatly enhanced by an intelligent combination of the large-scale numerical and physical simulations.

The main thrusts of this paper, then, are to demonstrate the rapid and continuing growth of computational aerodynamics, to indicate the principal areas that must be further developed if computational aerodynamicists are to provide significantly better tools for aeroelasticians, and to examine the requirements for a complete, time-accurate numerical simulation of the unsteady, transonic viscous flows around a realistic fighter aircraft configuration. This paper should be considered to be complementary to the broader, companion review of V. L. Peterson, entitled "Trends in Computational Capabilities for Fluid Dynamics" (Ref. 8), given earlier at this Specialists' Meeting. No attempt has been made to review comprehensively the large and rapidly growing body of literature on unsteady computational aerodynamics. Rather, our somewhat random and parochial choice of representative examples largely reflects the research with which we are most familiar and the results which are most readily available to us.

Presented at the AGARD Structures and Materials Panel Specialists' Meeting on "Transonic Unsteady Aerodynamics and Its Aeroelastic Applications," September 3-5, 1984.



ADVANTAGES

- EASILY APPLIED
- FEWEST RESTRICTIVE ASSUMPTIONS
- OPTIMIZATION LINK POSSIBLE
- COMPLETE FLOW FIELD DEFINITION
- TREATMENT OF COMPLICATED CONFIGURATIONS
- NO MACH NO. OR REYNOLDS NO. LIMITATIONS
- COST EFFECTIVE
- EASY TO CHANGE GEOMETRY

- REPRESENTATIVE OR ACTUAL CONFIGURATION
- REPRESENTATIVE AERODYNAMIC DATA
- OBSERVATION OF NEW FLOW PHENOMENA
- EASY TO CHANGE FLOW PARAMETERS

DISADVANTAGES

- INADEQUATE TURBULENCE MODELS
- LACK OF COMPUTER STORAGE AND SPEED
- ACCURACY OF FINITE - DIFFERENCE REPRESENTATIONS
- EXPENSIVE FOR MANY RUNS

- COSTLY MODELS AND TUNNEL TIME
- TUNNEL DEPENDENT FLOW CONDITIONS (WALLS, IMPURITIES, TURBULENCE, DISTORTION)
- LIMITED AMOUNT OF DATA
- ACCURACY OF DATA OBTAINED
- SCALING (VISCOUS EFFECTS, CHEMICAL NONEQUILIBRIUM, etc.)

USE BOTH TOGETHER

Fig. 1. Complementary tools for aeronautical design.

THE GROWTH OF CFD CAPABILITIES

An overall glimpse of the development of Computational Fluid Dynamics over the past 30 years, especially as applied to unsteady, external aerodynamics, is given in Table 1. Generally as new capabilities develop for treating nonlinear aerodynamics, their application to specialized unsteady problems (such as flutter) tends to lag behind the corresponding steady applications by about a decade. This is due partly to the additional difficulties of performing time-accurate calculations, as opposed to determining the harmonic components of the aerodynamic force coefficients by using linear theory; partly to the extra complication of coupling the unsteady airloads with the structural deformations of the vehicle; and partly to the relatively higher level of effort that has been expended toward predicting steady airloads and performance.

TABLE 1. STAGES OF COMPUTATIONAL AERODYNAMICS DEVELOPMENT INCLUDING UNSTEADY EFFECTS

Approximation level		Capability	Initiation time period	
			Research	Applications
I	Linearized inviscid	Subsonic, supersonic Pressure distributions Vortex and wave drag Flutter	1950s	1960s
II	Nonlinear inviscid	Above plus Transonic Hypersonic	1960s 1970s*	1970s 1980s*
III	Re-averaged Navier-Stokes model turbulence	Above plus Total drag Separated flow Stall buffet	1970s 1980s*	1980s 1980s*

Limitations: Computer size and speed
Turbulence modeling
[illegible]
Wing wake*

*Including unsteady effects

Before tracing the growth of specific CFD capabilities over the past decade, it is useful to bear in mind some of the special aerodynamic features [illegible], as illustrated in Fig. 2. For a given level of geometrical complexity, the most [illegible] tend to occur in the transonic flight regime, where nonlinear aerodynamics must be [illegible] the difficulties are generally compounded

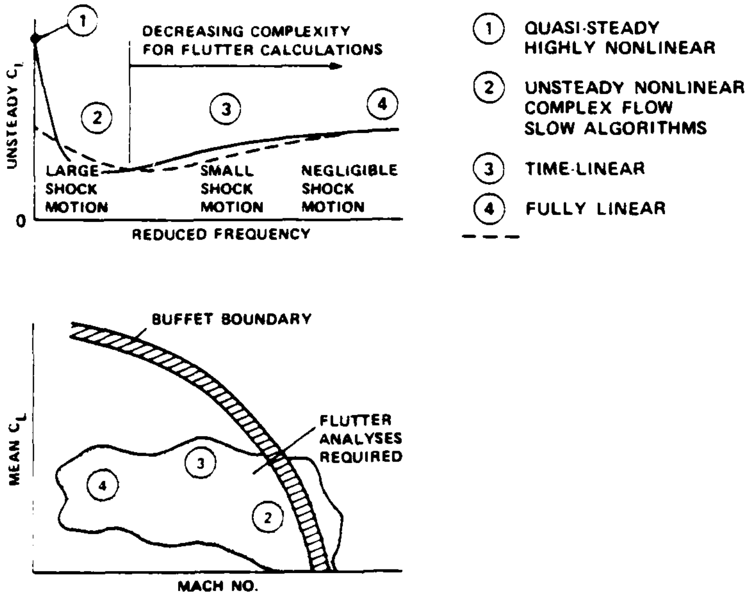


Fig. 2. Unsteady flow regimes for transonic wings.

at lower reduced frequencies, where the shock-wave motion is the largest and the resultant unsteady aspects of the fluid physics are the most complex.

Unfortunately, the current computational-aerodynamics codes that might be capable of capturing these low-frequency complexities tend to have severe stability limitations with respect to the maximum time step that can be used. This translates into long computational times per cycle of oscillation. In addition to purely financial reasons, long CPU time impedes progress in several ways. First, it discourages new users from trying unfamiliar codes and becoming comfortable with them; second, it discourages experienced users from experimenting with the codes in new applications; and third, it limits code developers in their efforts to refine, tune, and extend the methods.

An impractical conclusion that could be drawn from Fig. 2 is that aeroelastic analyses would be simplified if the vehicles were restricted to subsonic speeds, or if the natural frequencies of the structures could be increased by an order of magnitude.

2.1 Representative Calculations — 1974 and 1984

A better understanding of the current trends in computational aerodynamics can be obtained by tracing the growth in capabilities that has occurred over the past decade. In this section we will note a few examples that were particularly noteworthy as state-of-the-art circa 1974, and discuss the corresponding capabilities today.

2.1.1 Steady flow, complex geometries

For many years, linear panel methods have been the primary tool for analyzing complete vehicles of complex geometry. Figure 3 illustrates the degree of sophistication that has been and is possible. Larger computers have enabled the use of more panels, with a corresponding improvement in the resolution of the surface airloads. However, the primary advance in panel methods since 1974 is the present capability to treat supersonic problems with the same surface representation that before could be done only for subsonic cases. Figure 4 shows representative results (Ref. 9) for a fighter configuration with canards. The lift of the aircraft is well predicted, but further improvements are required for predicting the drag.

Insofar as nonlinear methods are concerned, three-dimensional transonic small-disturbance calculations of wing-body combinations were possible with the Bailey-Ballhaus code (Ref. 10) a decade ago. More complicated configurations are routinely analyzed with full potential methods today, and Euler methods are coming to the forefront; e.g., Refs. 11-13. Figure 5 shows the recent calculations of Jameson and Baker (Ref. 11). These results have not been verified by independent calculations or comparison with experiment, and the very coarse grid on the tail surfaces is probably inadequate for resolving the flow in that region. However, the influence of the body and tail on the flow over the wing is probably captured accurately enough in this simulation.

2.1.2 Complex steady flow, simple aerodynamic shapes

Jameson's FLO6 transonic potential-flow code (Ref. 14) for airfoils with shock waves came into general use in the early 1970s; and by 1974, weak viscous corrections had been added (Ref. 15). With regard to viscous-dominated flows, in that era Mehta (Ref. 16) treated the fully separated flow of an airfoil at high angle of attack using the laminar Navier-Stokes equations, and computed the self-induced fluctuations as well as the mean airloads. Today the stalled airfoil at high Reynolds numbers remains an unsolved problem, but this is mainly because of the turbulence modeling, and not because of the computational barriers.

A decade ago Deiwert (Ref. 17) treated shock-induced separation on a nonlifting airfoil with the Reynolds-averaged Navier-Stokes equations, using an algebraic mixing-length model of the turbulence. That

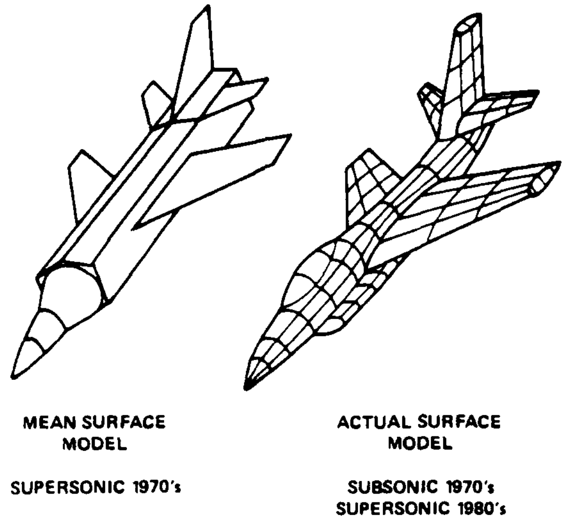


Fig. 3. Surface panel geometries for linear calculations.

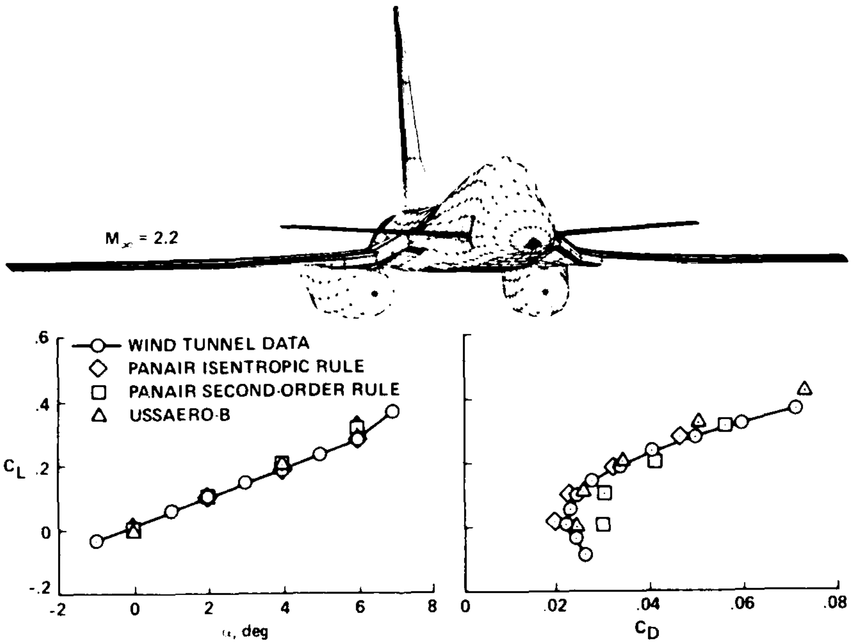


Fig. 4. Panel methods applied to a supersonic fighter aircraft (Ref. 9).

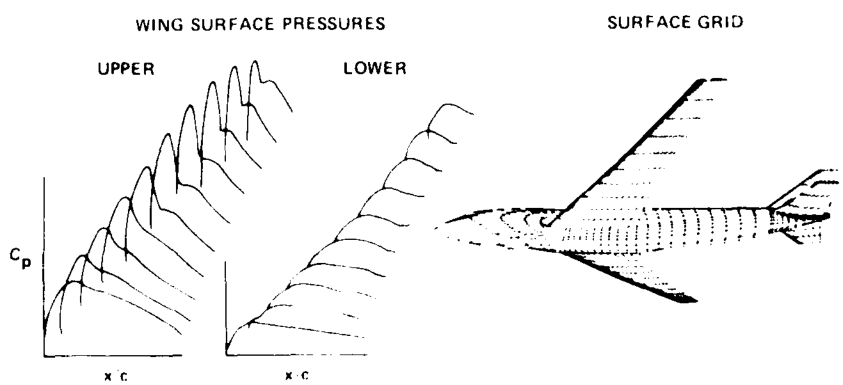


Fig. 5. Euler calculations of a wing-body-tail combination (Ref. 11); $M_\infty = 0.84$, $\alpha = 2.44°$, 96 × 16 × 16 grid.

capability has since been extended to a lifting transonic wing by Mansour (Ref. 18), including both shock waves and tip vortex formation (Fig. 6), and to afterbodies with propulsive jets by Deiwert and Rothmund (Ref. 19) (Fig. 7).

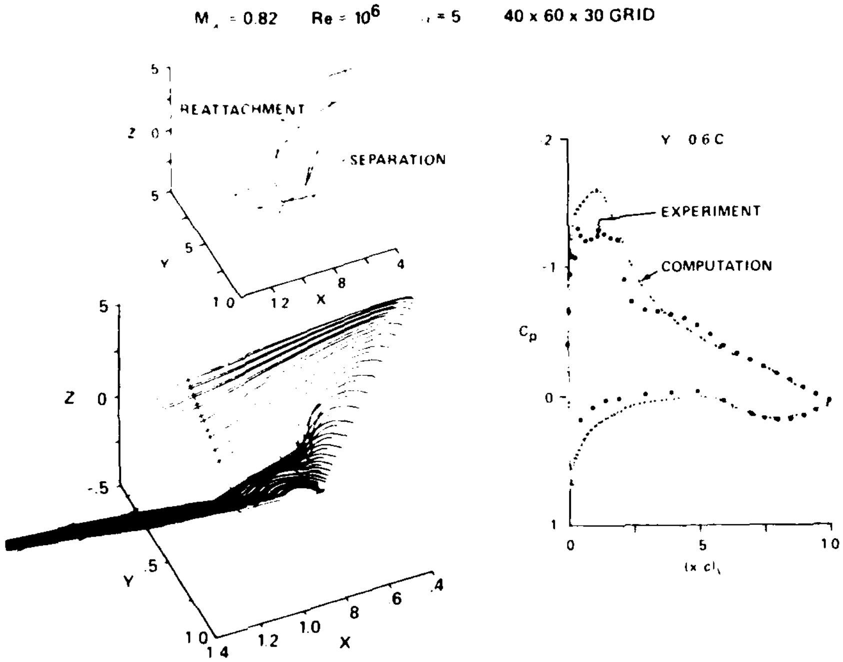


Fig. 6. Thin-layer, Reynolds-averaged Navier-Stokes calculations of a wing in transonic flow (Ref. 18); M_∞ = 0.82, Re = 10^6, α = 5°, 40 × 60 × 30 grid.

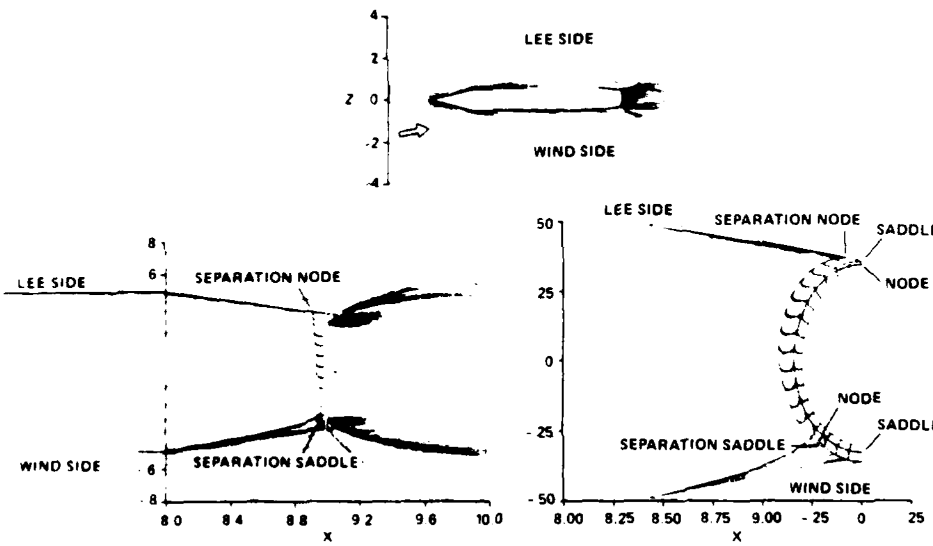


Fig. 7. Thin-layer, Reynolds-averaged Navier-Stokes calculations of a conical afterbody with a propulsive jet (Ref. 19); M_∞ = 2.0, α = 6°, M_j = 2.5, Re = 1.5 × 10^6, 140 × 100 × 20 grid.

Although Mansour's wing calculations were performed on a relatively coarse grid, several hours of CPU time were required to obtain the results shown in Fig. 6. Furthermore, the agreement with the experimental data is only fair, and probably 10 times as many grid points would be required to resolve the details of the flow. Nevertheless, this investigation represents a milestone in analyzing viscous wing flows.

The afterbody calculations shown in Fig. 7 provide a remarkable amount of detail by using only a modest number of grid points. This capability stems from a high degree of specialized experience with this particular code and this particular class of problems, and it illustrates the value of having skilled experts to work with a family of codes. Even so, difficult cases with larger separation zones still give problems (Ref. 20).

2.1.3 Unsteady inviscid flow

One of the showcase results of the mid-1970s was the calculation of Magnus and Yoshihara (Ref. 21) for an oscillating airfoil with a strong shock wave, using an explicit Euler method (Fig. 8). Another

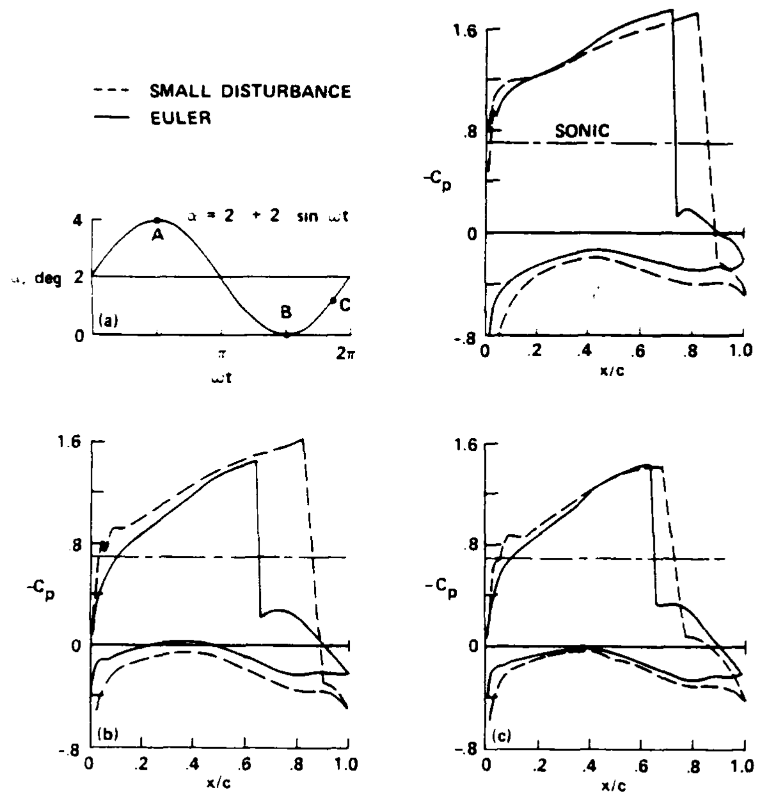


Fig. 8. Euler calculations of a transonic oscillating airfoil (Ref. 21); NACA 64A-410 airfoil, M = 0.72, $\omega c/U_\infty$ = 0.20.

pioneering set of results was obtained by Caradonna and Isom (Ref. 22), using a three-dimensional, unsteady transonic small-disturbance code, shown in Fig. 9. The two-dimensional small-disturbance code LTRAN2 (Ref. 23) also became available soon afterward, and it has been used extensively ever since. Each of these helped pave the way for the computational capabilities that exist today, and they provided insights into unsteady effects that could not have been obtained either by linear theory or by experiments.

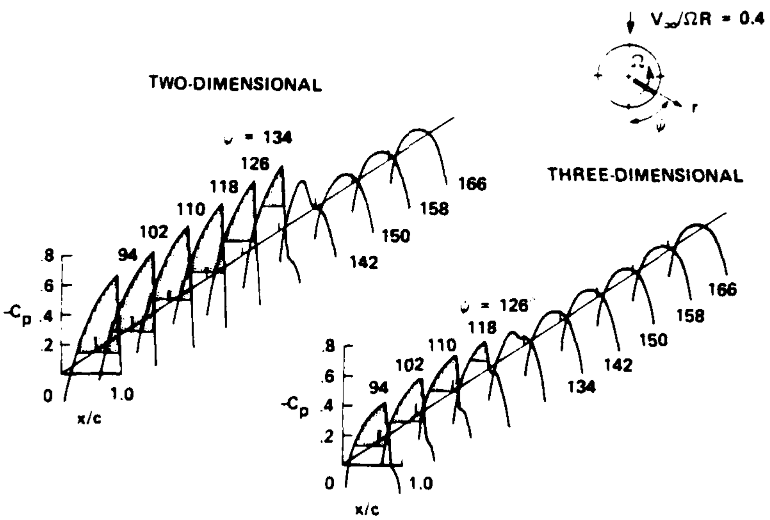


Fig. 9. Transonic small-disturbance calculations of a nonlifting helicopter blade tip (Ref. 22).

The unsteady transonic small-disturbance method has since achieved a high level of maturity in both two and three dimensions. Also, approximate viscous corrections have been added, and the aerodynamic calculations have been coupled with the structure (Refs. 24-27). Figure 10 shows the results of Guruswamy and Goorjian (Ref. 27) for a low-aspect-ratio oscillating wing. These calculations, using 51,200 grid points and 1024 time steps per cycle, required about 30 min of CPU time on a Cray XMP computer to compute three cycles of oscillation.

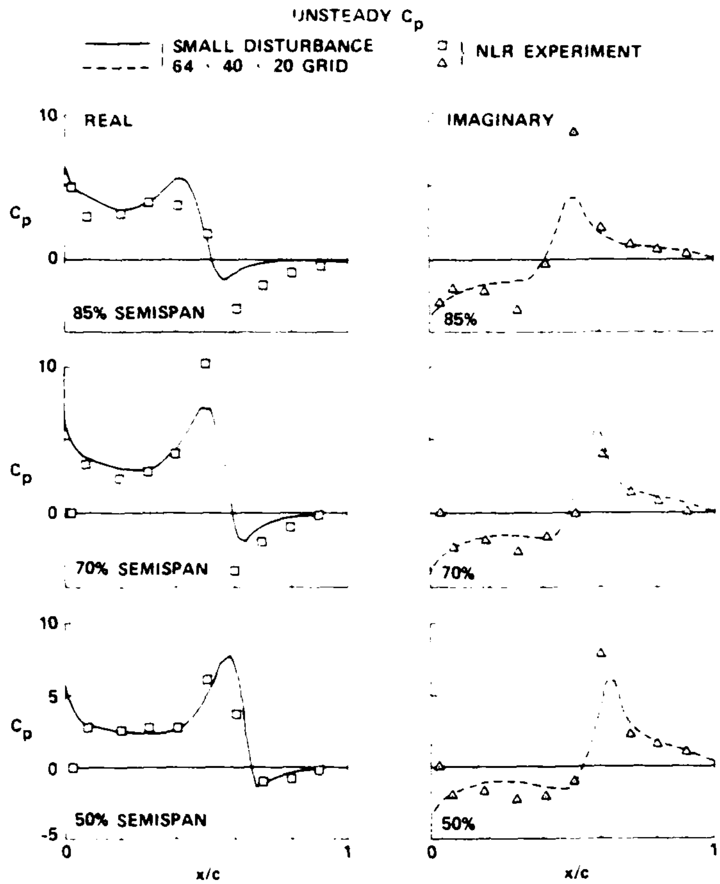


Fig. 10. Transonic small-disturbance calculations of the oscillating F-5 wing (Ref. 27); $M = 0.90$, $K = \omega c/U_\infty = 0.55$.

The full-potential results of Malone et al. (Ref. 28) for the same oscillating wing are shown in Fig. 11. In this case, only 18,000 grid points were used, with correspondingly less resolution. The calculations required several hours on a VAX 11/780 computer. Finally, the full-potential calculations by Isogai and Suetsugu (Ref. 29), for wings with part-span oscillating flaps, may also be mentioned to illustrate the current capabilities for inviscid flows.

2.1.4 Unsteady viscous flow

Although unsteady effects on turbulent boundary layers were computed by several investigators in the early 1970s, there were essentially no unsteady viscous results available 10 years ago that were of direct interest to aeroelasticians. Today we can point to studies of oscillating airfoils and flaps using the Reynolds-averaged Navier-Stokes equations with simple eddy-viscosity turbulence models that can be run in an hour or less on modern supercomputers. As an example, the calculations of Horiuti et al. (Ref. 30) are shown in Fig. 12. This investigation also includes a study of the effects of wind-tunnel walls, which can significantly alter the phase of the unsteady pressure distribution behind the shock wave.

Another recent Navier-Stokes calculation at transonic speed and a high Reynolds number (Fig. 13), from Ishii and Kuwahara (Ref. 31), illustrates the growing CFD capability in Japan. It is interesting to note that these results, which have not been validated by experimental comparisons, were obtained with no turbulence model at all. Finally, the recent review of compressible Navier-Stokes solutions by Shang (Ref. 32) may be consulted for further examples and for a comprehensive bibliography.

2.2 Cost and Capability Trends

The preceding examples indicate the growing capabilities to solve challenging aerodynamics problems. Much of this progress can be traced directly to the extraordinary growth in computer technology, as discussed in Refs. 1-8. Computer speed, memory size, and cost are all important factors in assessing the present and future capabilities for performing complex aeroelastic analyses. An overview of the trends for these factors is given in Figs. 14-16, from Peterson (Ref. 8).

Figures 14 and 15 show that speed and memory capacity continue to grow more rapidly than the costs of the machines. Consequently, the relative cost of performing aerodynamic calculations is decreasing dramatically (Fig. 16). The improvements in algorithms and methods of analysis are more difficult to quantify than are those in hardware; but the general trends are clear, and researchers are confident of further gains. The net result is that the cost of performing a given computation has decreased three or more orders of magnitude per decade (Refs. 6-8), and this trend is projected to continue for some time.

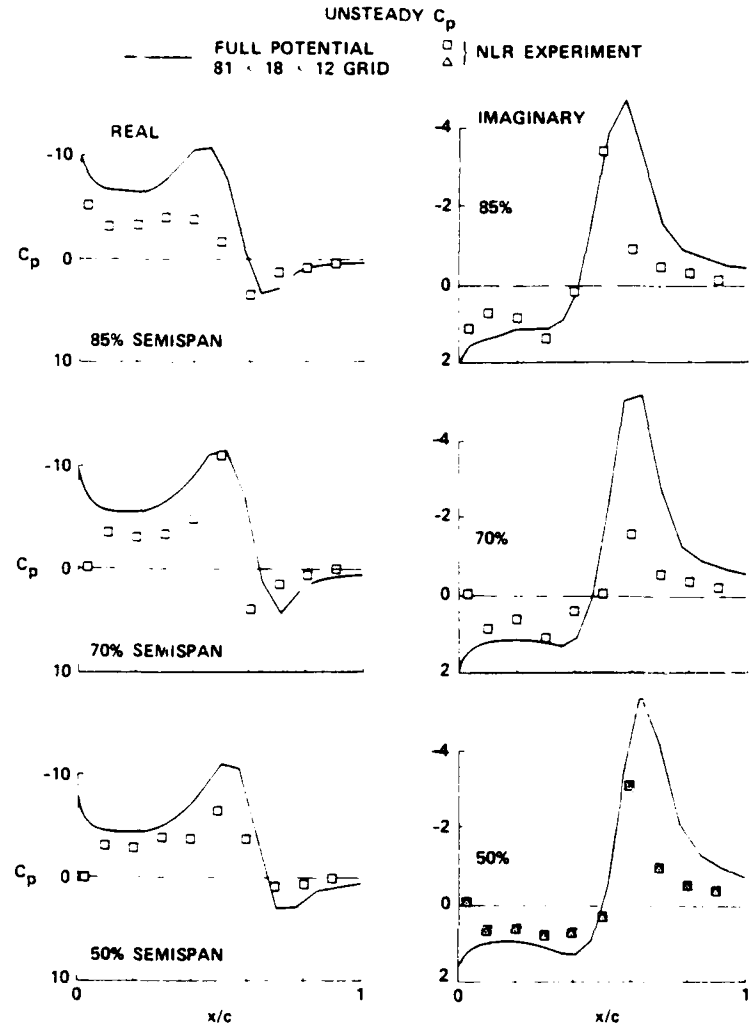


Fig. 11. Unsteady full-potential calculations of the oscillating F-5 wing (Ref. 28); $M = 0.90$, $K = \omega c/U_\infty = 0.55$.

An even more important trend, which is difficult to portray graphically, is the strong tendency to attack increasingly difficult problems (and with greater confidence) as speed, memory, numerical methods, and physical modeling improve. To paraphrase the oral version of Ref. 3, concerning the impact of CFD on commercial aircraft design,

> The total costs of computing have gone up, not down—we just do a lot more CFD than ever before in the quest for superior, innovative designs.

This trend is also implicit in MacCormack's prediction (Ref. 33) that a Reynolds-averaged Navier-Stokes solution for a complete aircraft will be obtained in 1985.

2.3 Summary of Current Status

The growth of CFD over the past decade has given us adequate capabilities to model compressible flows with imbedded shock waves and weak viscous effects (i.e., at low angle of attack and without shock-induced separation). This can be done on simple, but practical, bodies undergoing small-amplitude motions, in free air or solid-wall wind tunnels. However, many of the codes have not been adequately validated and calibrated. Also, we still have, at best, only marginal capabilities for strong vortices, strong turbulent viscous effects, complex geometries in the transonic regime, or simulation of ventilated-wall wind tunnels.

The combined hardware and software costs of computing today's problems are not trivial, especially when user-manpower costs are included. However, the relative costs of computations have dropped steadily by a factor of about 1000 per decade over the past 20 years. In addition, the growth in capability and the reduction in turn-around time for a typical calculation are even more important than the cost trends to many segments of the aircraft industry. Except for the limitations of turbulence modeling, the showcase problems of 1974 can be solved routinely in 1984.

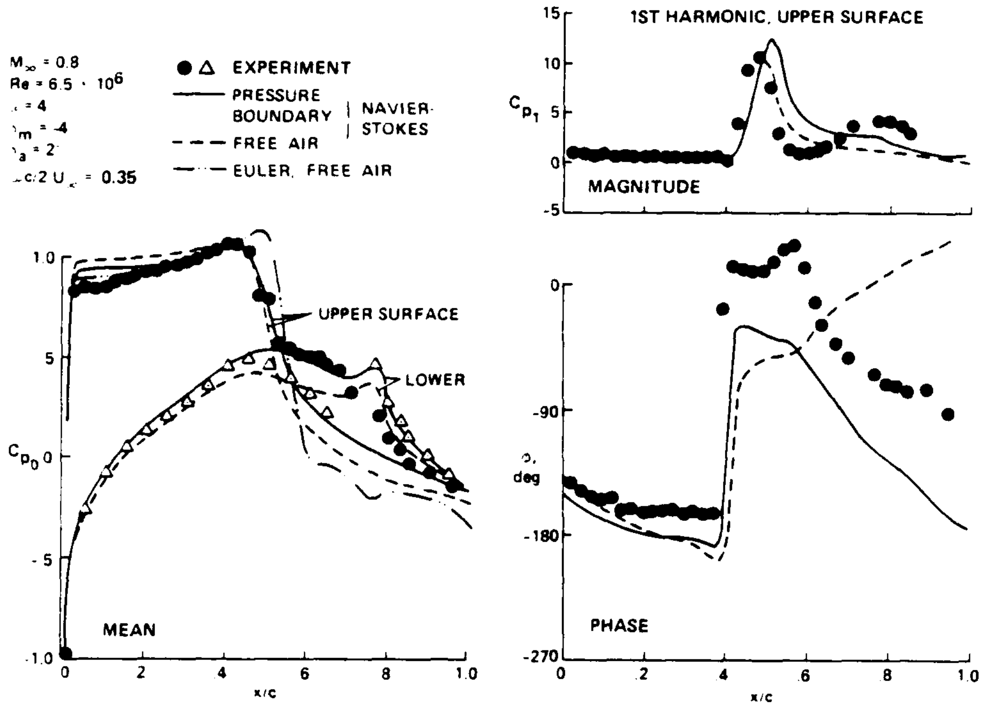


Fig. 12. Transonic viscous flow over an airfoil with an oscillating flap (Ref. 30); 139 × 49 grid.

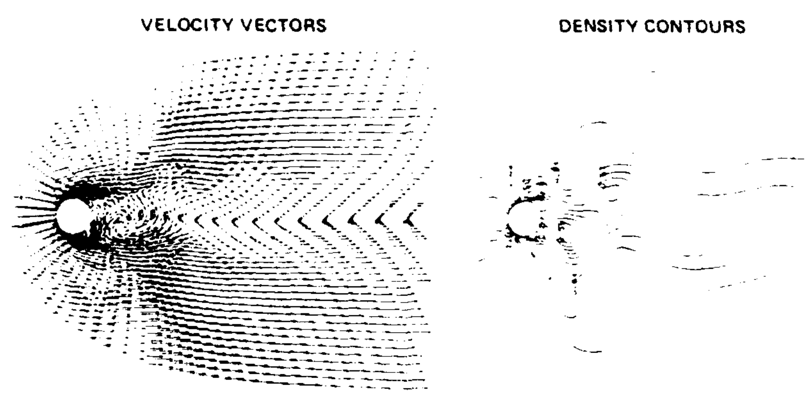


Fig. 13. Compressible flow around a circular cylinder at $M = 0.8$ and $Re = 5 \cdot 10^6$ (Ref. 31), 121 × 60 grid.

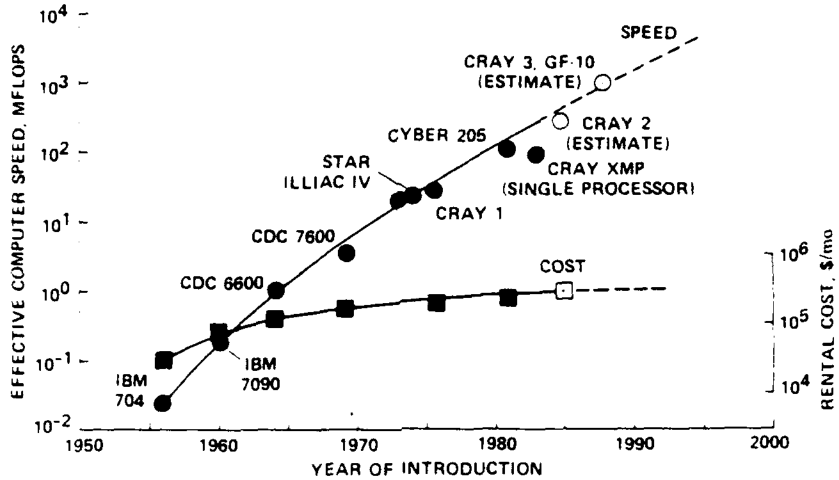


Fig. 14. The growth of computer speed and cost (Ref. 8).

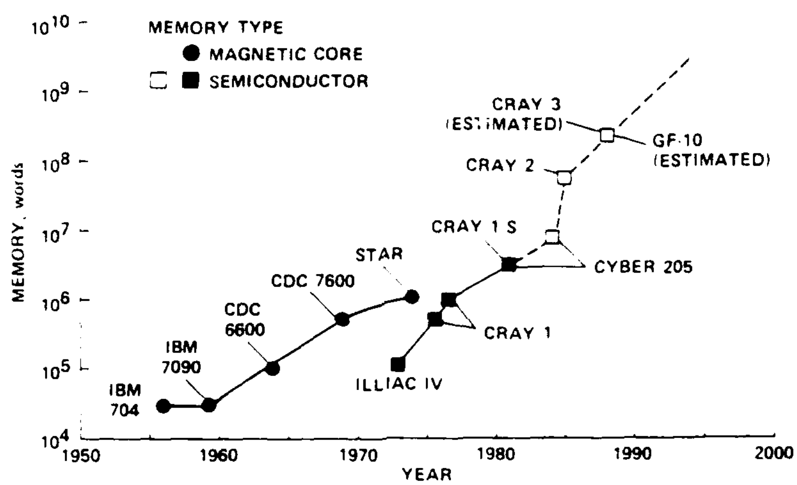


Fig. 15. The growth of computer memory (Ref. 8).

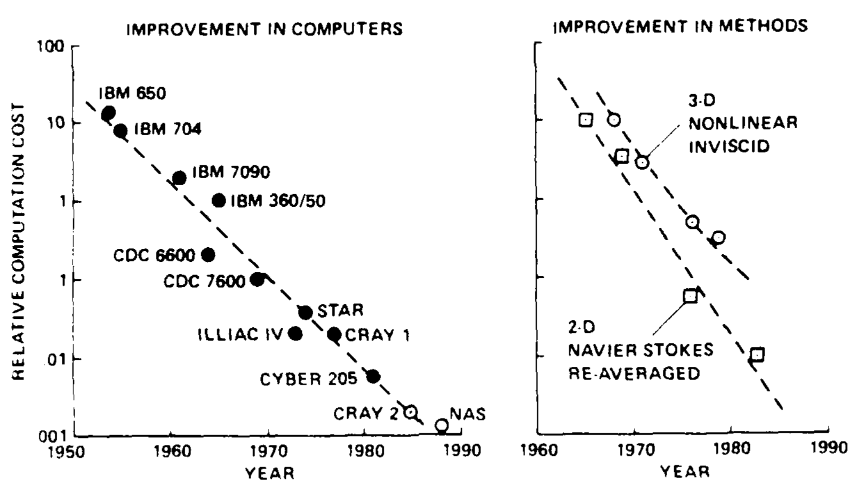


Fig. 16. Cost trends of numerical simulations (Ref. 8).

3. THE CHALLENGES FOR AEROELASTIC APPLICATIONS

Despite the progress that has been made in computational aerodynamics, there are definite limits to what can be done practically, especially in aeroelastic applications. Also, the computing cost for the aerodynamics part of a typical flutter simulation for a complex vehicle flying at transonic speeds could exceed the structural-dynamics part by a considerable margin. In this section, we turn to some of the pacing items and current limitations of CFD as they relate to aeroelastic problems. We shall also consider the extent to which some of these limitations might be relaxed or eliminated, and indicate some areas in which new developments could pay rich dividends.

3.1 Limiting Factors for Computational Aerodynamics

Figure 17 illustrates the most important pacing items in applying computational aerodynamics to aeroelastic problems. Grid generation, turbulence modeling, and computer hardware and software were identified in Refs. 5 and 6 as primary pacing items, and this will remain true for the foreseeable future in almost all areas of CFD. Current applications are limited by both computer speed and memory; the relative importance of each can be debated for aircraft performance predictions and design. However, as we shall see, the roles of the algorithm and solution methodology tend to be more important in time-dependent problems than in steady-flow predictions. This is because smaller time steps are often needed for stability considerations than for accurately capturing the unsteady features of the flow.

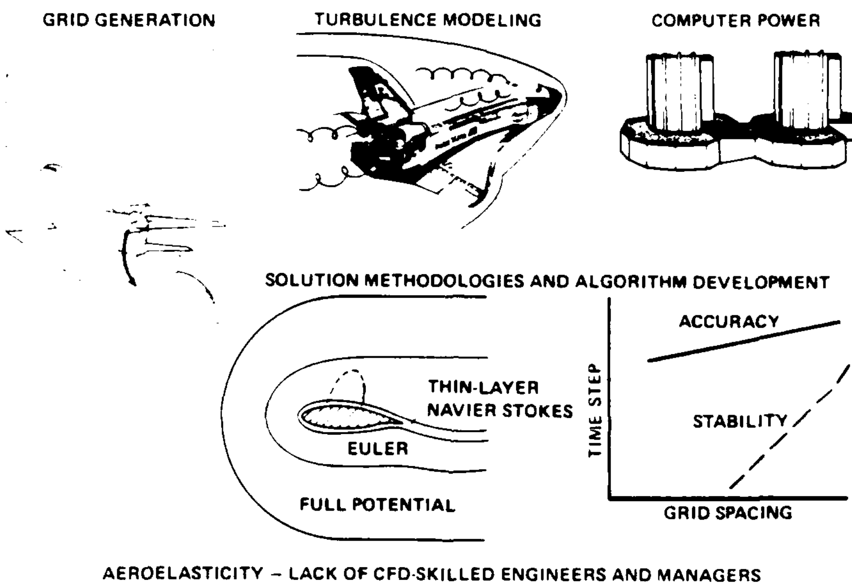


Fig. 17. Pacing items in computational fluid dynamics.

Another novel aspect of aeroelasticity is less of a technical issue than a management one; namely, the shortage of engineers and research scientists who are specialists in both computational fluid dynamics and structural dynamics. To a certain extent, the rate of progress can be expected to be proportional to the level of effort expended and to the skills of the people exerting the effort. In addition, there are even fewer managers who have been trained in both these disciplines.

Insights into the magnitude of the challenges, and prospects for nonlinear aeroelastic applications, can be obtained by analyzing the factors that determine the solution times, or CPU requirements, for a typical time-accurate, unsteady airloads calculation. For most CFD methods, the CPU time can be expressed as

$$CPU = A \times W_{GT} \times N_G^m \times N_T/FLOPS$$

where

A = "numerical inefficiency" factor

W_{GT} = number of operations per grid point per time step

N_G = number of grid points

m = 1 for finite-difference, ≈2 for panel methods

N_T = number of time steps = (number of time steps/cycle) × (number of cycles) = (number of reference lengths/cycle) × (number of cycles)/$\Delta\tau$

τ = nondimensional time step = $U_\infty \Delta t/L$

FLOPS = number of floating-point arithmetic operations per unit time

Here we introduce the efficiency factor A, to emphasize that the code may not take full advantage of the computer being used; in practice it is a function of the programming efficiency, the degree of vectorization, the coupling between the grid and the solution algorithm, the user experience, etc. Ideally, its value should approach unity; but especially with the advent of supercomputers with novel architecture, it could be much larger.

The number of arithmetic operations per grid point per time step, W_{GT}, is a strong function of the numerical method; that is, of the flow equations, the boundary conditions, the solution algorithm, and the grid. The quantity N_G represents the number of grid points for a finite-difference method, the number of elements for a finite-element method, or the number of panels for a panel method. Consequently, $W_{GT}N_G$ represents the number of arithmetic operations that must be performed at each iteration or time step; although, in some instances with panel methods, $N_G \log N_G$ is a more accurate representation than N_G^2.

Ideally for aeroelastic applications, the total number of time steps, N_T, would simply be the number of time steps per cycle multiplied by the number of cycles needed to determine the flutter characteristics. However, many nonlinear aerodynamics codes have stability or accuracy limits that are determined by a nondimensional time step, $\Delta\tau = U\,\Delta t/L$. Thus the maximum permissible value of $\Delta\tau$ typically depends upon the complexity of the problem, the algorithm, the grid, and the desired accuracy.

Finally, the computing speed, FLOPS, is a function of the computer clock speed and architecture, the data management techniques of the code, the memory requirements (in-core or external memory), and the solution algorithm. Thus it is clear that many different factors determine the CPU time, and the cost, of an aerodynamic calculation.

Estimates have been made of the solution times that would be required to run a wide range of contemporary time-accurate methods on modern supercomputers. Table 2 shows a breakdown of the factors in Eq. (1) for a wing of moderate complexity undergoing three cycles of oscillatory motion and 25 chord lengths of travel per cycle, running on a computer with a nominal sustained rate of 80 million floating-point operations per second. By "moderate complexity," we mean something a bit more complicated than the wing shown in Fig. 6. This might include, for example, a relatively clean wing-body combination, a wing with a flap, a wing with a tip tank or tip-mounted rocket, etc., but not a wing with multiple external stores. Other assumptions are noted in the notes to Table 2.

TABLE 2. COMPUTATIONAL REQUIREMENTS FOR COMPLEX OSCILLATING WINGS

Flow model	W_{GT}	N_G	$\Delta\tau$	CPU, minutes	Memory, million words	Notes
Nonlinear panel	$W_{GT} \cdot N_G^m = 2 \times 10^8$		0.05	60	2.0	a,c
Small disturbance	100	10^5	0.06	8	0.6	b,d
Full potential	600	10^5	0.04	23	2.0	d,e
Full potential and integral B.L.	630	10^5	0.02	50	2.0	d,e,f
Euler	3000	10^5	0.01	450	3.0	d,e
Euler and finite difference B.L.	2000	2×10^5	0.01	600	6.0	d,e,g
Thin-layer Navier-Stokes	3600	10^6	0.005	11,000	30	d,e
Reynolds-averaged Navier-Stokes	4500	2×10^6	0.004	35,000	60	d,e

Notes:
a. A = 2
b. A = 3
c. $\Delta\tau$ for time accuracy
d. $\Delta\tau$ for stability limitations
e. W_{GT} includes 100 for grid generation
f. 5% increase in W_{GT} for boundary layer
g. W_{GT} = 500 in viscous layer, 3000 in inviscid region

It should be mentioned that a time step limit of $\Delta\tau = 0.05$ has been assumed as a rather subjective estimate of what is required to resolve accurately unsteady transonic effects, including significant shock wave motion. For cases which can be considered as almost linear perturbations about a nonlinear mean flow, much larger values might suffice. We also acknowledge that our estimates of the stability limitations on $\Delta\tau$ are very approximate, and the numbers given are intended to give a sense more of the relative values of the various methods than of the absolute values. The important point is that, currently, the more sophisticated the method, the more severe is the stability restriction on $\Delta\tau$ for highly nonlinear problems.

The solution-time requirements are compared graphically in Fig. 18. We note again that all of these results are very approximate, accurate to one significant figure at best. In Fig. 18, the "time-linearized" estimate refers to any of the numerous methods that are available for obtaining the harmonic components of the unsteady airloads as a linear perturbation about a nonlinear mean-flow condition; i.e., Regime 3 in Fig. 2. The estimates for the nonlinear panel methods (which are based on Refs. 34-36, and private conversations with Forrester Johnson of the Boeing Military Airplane Company and Larry Erickson of NASA Ames) are even more approximate, as these methods have not yet been used to calculate the time-accurate evolution of transonic flow fields.

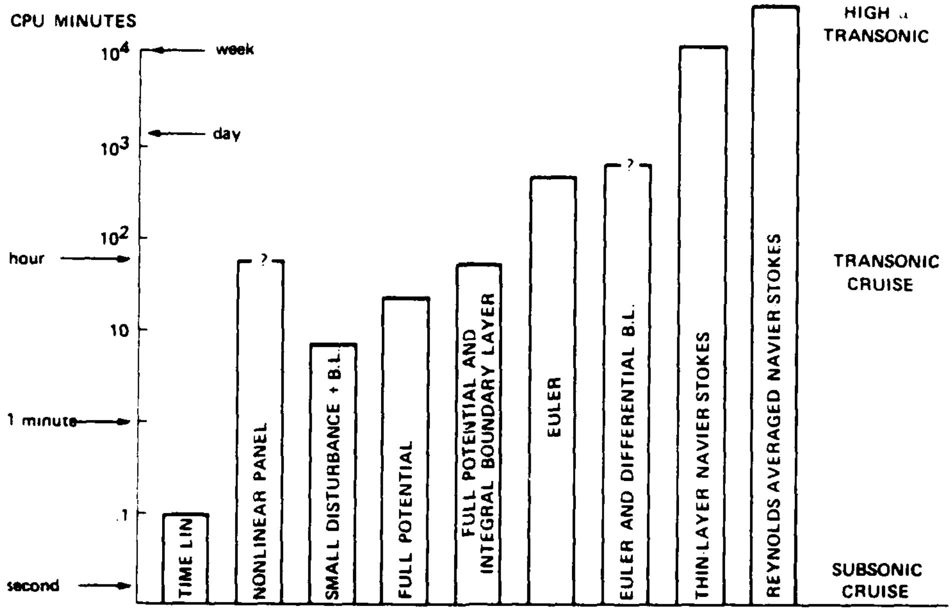


Fig. 18. Solution times for a wing of moderate complexity; 75 chords travel/case, 1984 algorithms, 80 mflops.

Similarly, the estimates for combining an Euler method and finite-difference boundary layer are purely speculative. They are based on the work of Van Dalsem and Steger (Ref. 37) with the steady full-potential equation, and private conversations with them; however, this approach has yet to be implemented in an actual unsteady, three-dimensional code. The basic concept is very attractive, however. The additional number of grid points in the viscous layer and wake is assumed to be the same as the number in the inviscid field, but the number of arithmetic operations per viscous grid point is only about 600. Therefore, the average value of W_{GT} decreases for the coupled system of equations, and the product of W_{GT} and N_G increases only about 30%.

The information in Table 2 and Fig. 18 implies that if the transonic effects are mild enough to fall within the scope of the time-linearized methods, then extensive flutter analyses are probably affordable now. But time-accuracy is expensive today for any nonlinear method, and is probably prohibitively so for anything more sophisticated than the potential methods. This raises the question of what can be done, or what is likely to be done, over the next few years to bring the costs of all the methods down to acceptable levels.

3.2 Targets of Opportunity

Independent of the efforts of the CFD and aeroelasticity communities, supercomputer technology can be expected to increase the computation speeds from 80 to 250 mflops or more, within the next 3 years, and to provide adequate memory to meet the requirements listed in Table 2. In addition, a number of specific improvements can be readily foreseen in computational aerodynamics. Although many of these improvements will take significant amounts of time and effort to develop and to validate, they represent advances that are within our grasp.

3.2.1 Algorithm and numerical technique improvements

Equation (1) provides the basis for assessing the possibilities of significantly reducing the CPU times for the various time-accurate methods. The main thrusts should obviously be to reduce the total number of floating-point operations for each time step, as indicated in Table 3, and to decrease the total number of time steps by increasing $\Delta\tau$ (Table 4). In the following discussion, it will be assumed that the previous upper limit of $\Delta\tau = 0.05$, based on accuracy considerations, can be increased to 0.10 by a combination of experience and improved grid techniques.

Nonlinear panel methods – These methods have been under development for steady flows, where multi-grid techniques are useful (Refs. 34 and 36). They would seem to be candidates for significant reductions in the number of iterations required per time step, and for reducing the dependence on the number of surface panels or field grid points to perhaps $N_G^{1.2}$ or $N_G \log N_G$, instead of N^2. Also, it should be possible to increase the time step limit to 0.1, as noted above, and to remove the stability restrictions that seem to affect current integral boundary-layer treatments of viscous effects.

Transonic small disturbance methods – On the other hand, this approach has already matured to the point where the number of arithmetic operations required is not likely to decrease significantly below current levels. Room for improvement exists primarily in decreasing A to unity by rewriting the existing codes (Refs. 24 and 26), and by increasing $\Delta\tau$, as above. This can probably be done by treating more of the "secondary" terms implicitly instead of explicitly. With additional experience, the same accuracy can probably be attained with a 30-50% reduction in the total number of grid points, with a corresponding reduction in CPU time.

TABLE 3. REDUCING COMPUTATION TIMES

$A \times W_{GT} \times N_G^m$ = effective total operations/time step

Flow model	Today ops/time step	Future
Nonlinear panel	2×10^8	Reduce m Reduce W_{GT} to 1 iteration/time step
Small disturbance	3×10^7	Reduce A to 1.0
Full potential	6×10^7	Reduce N_G by 50% with grid adaption
Euler implicit	3×10^8	Reduce W_{GT} by algorithm
Euler implicit plus boundary layer	4×10^8	Reduce N_G by grid adaption
Euler explicit	0.8×10^8	Reduce N_G by grid adaption
Thin-layer Navier-Stokes	4×10^9	Reduce W_{GT} by algorithm
Reynolds-averaged Navier-Stokes	9×10^9	Reduce N_G by grid adaption and zonal modeling

TABLE 4. REDUCING COMPUTATION TIMES

$N_R/\Delta\tau$ = total number of time steps

Flow solver	$\Delta\tau$ today	Future improvements
Nonlinear panel Small Disturbance Full potential	0.05 inviscid 0.02 B.L.	Increase to 0.1 by experience and grid adaption
Euler implicit (includes B.L.)	0.02 (stability)	0.10 (remove stability limit)
Euler explicit	0.01 (stability)	0.02 (increase Δx)
Navier-Stokes implicit	0.005 (stability)	0.1 (remove stability limit)

Full potential methods – The two main ways to improve this approach are to reduce the number of grid points required by using solution-adaptive grids, without increasing W_{GT}, and to increase $\Delta\tau$ by means of the better grids. A likely additional improvement will be to include an integral unsteady boundary layer formulation, with negligible increase in W_{GT} and with no stability restriction on $\Delta\tau$.

Euler methods – It may be possible to reduce the value of W_{GT} by about a third for this approach, and to halve N_G by the use of solution-adaptive grids, as discussed below. For the implicit methods, the severe time-step stability limitation should disappear. For the explicit methods, however, it is inherent and will remain a severe handicap. On the other hand, the successful coupling of finite-difference boundary-layer methods, as discussed above, seems likely, and this additional capability will undoubtedly be very attractive to future users.

Thin-layer and full Reynolds-averaged Navier-Stokes methods – These methods are considered together because of their similar numerical characteristics. The main difference is that the thin-layer approximation neglects the second derivatives in the streamwise flow direction, thereby reducing W_{GT} by about 20%. It should be noted that any techniques for reducing W_{GT} and N_G that are developed for the implicit Euler methods above probably would be applicable here, too. However, the greatest gains will come from removing the stability limit on $\Delta\tau$, which could then be increased by up to two orders of magnitude.

In practice, the principal reason for going to the full Navier-Stokes method would be to capture some separation phenomenon for which a finer grid in the streamwise direction would be required. This is reflected in the larger value of N_G, which is the main factor that makes the CPU time for full Navier-Stokes so much greater than for the thin-layer approach.

Figure 19 shows the reductions in CPU times that could accrue from the algorithm improvements outlined above, plus the effect of increasing FLOPS from 80 million to 250 million. In all cases, the number of grid points has been halved, and the limit on $\Delta\tau$ has been increased to 0.10.

It appears that the nonlinear potential-flow methods will become very economical, and that the more sophisticated methods will no longer be out of the question for specialized aeroelastic analyses. Of course, Fig. 19 does not show the important factor of how rapidly the improvements can be realized in practice. For example, the potential improvements of the small-disturbance approach are less, but they can be attained much quicker, than those of the Euler and Navier-Stokes methods. Therefore, we must reiterate that the range of flow models described above represents widely different levels of maturity and, hence, levels of confidence that aeroelasticians are likely to ascribe to them in practical applications. This would seem to suggest that the small-disturbance and full-potential codes will remain much more popular for the next few years, despite the growth in speed and memory of the new supercomputers.

However, once they have been validated, the Euler and Navier-Stokes codes will help to provide new understanding of and insights into complex flow phenomena, as well as to generate data bases which can be

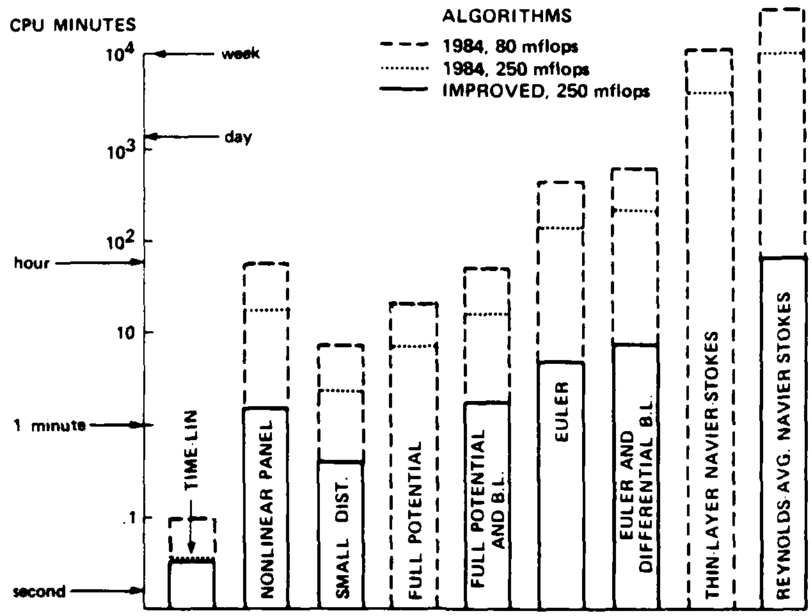


Fig. 19. Projected solution times for a wing of moderate complexity; 75 chords travel/case, improved algorithms, 250 mflops.

used to develop greater confidence in any of the more approximate methods. If this new capability is properly combined with careful wind tunnel experiments, a major surge in unsteady computational aerodynamics can be expected in the late 1980s, and the projections listed in Table 1 will turn out to be pessimistic.

3.2.2 Grid generation improvements

An essential step in solving three-dimensional aerodynamic problems is the generation of a suitable grid. This is one of the most rapidly growing areas of CFD, and there have been several meetings in recent years devoted exclusively to grid generation; e.g., Refs. 38 and 39. The recent survey by Thompson (Ref. 40) is particularly noteworthy, and a broader overview can be found in Ref. 5.

Several contemporary concepts for generating grids are illustrated in Fig. 20. A significant advantage of some panel methods, and of the transonic small-disturbance method, is that the appropriate boundary conditions can be applied on nonaligned grids; however, most of the more sophisticated methods rely on body-conforming grids. The zonal modeling, or multi-block concept, appears especially attractive for complex configurations.

The schemes for generating grids can be classified into two categories, algebraic and differential, based on the types of equations that are used to compute the locations of the grid points. Although the complexity may vary greatly, the algebraic methods are direct approaches. The differential methods involve the solution of either the elliptic, hyperbolic, or parabolic partial differential equations; this is done iteratively in the elliptic schemes, or noniteratively in the hyperbolic and parabolic schemes. References 5 and 40 include discussions on the degree of control that each method provides for varying the mesh spacing, cell volumes and proportions, and skewness of the grid lines. The elliptic and "nonconformal" algebraic schemes allow exceptionally high-quality grids to be generated about very general body shapes, but they are the most computationally intensive and expensive. For this reason, the more simple types of algebraic schemes and hyperbolic schemes seem better suited to the class of unsteady problems that requires regenerating the grid at each time step.

The concept of adapting the grid to some feature of the solution, such as clustering grid points in regions of large gradients, has considerable potential for obtaining the maximum accuracy with the least number of grid points. Therefore, this is an area of active research in the CFD community. As an example, Fig. 21 shows a solution-adapted grid and the associated laminar Navier-Stokes results (Ref. 41) for an unusual bluff body. The hyperbolic scheme that was used in adapting the inner grid to the developing vorticity field required only a small increase in the CPU time, due to the relatively small increase in W_{GT}; but it permitted considerably better resolution of the flow field to be achieved near the corner of the body. It is work of this type that leads us to believe that the grid point requirements, and hence the CPU times, can be reduced by a factor of two or more without sacrificing accuracy, as presented in Section 3.2.1.

3.2.3 Turbulence modeling

The simulation of the dynamics of turbulence remains the foremost challenge in fluid dynamics today, and turbulence modeling is probably the weakest link in the chain of computational aerodynamics technology. The computational power available in the foreseeable future, in terms of both speed and storage, will preclude adequate resolution of the broad range of interacting turbulent scales (both spatially and temporally) associated with most aerodynamic flow fields at flight Reynolds numbers. As a result, turbulence modeling has taken the approach of single-point closure of the Reynolds-averaged Navier-Stokes equations, and no single turbulence model exists that can be applied to a general variety of flows.

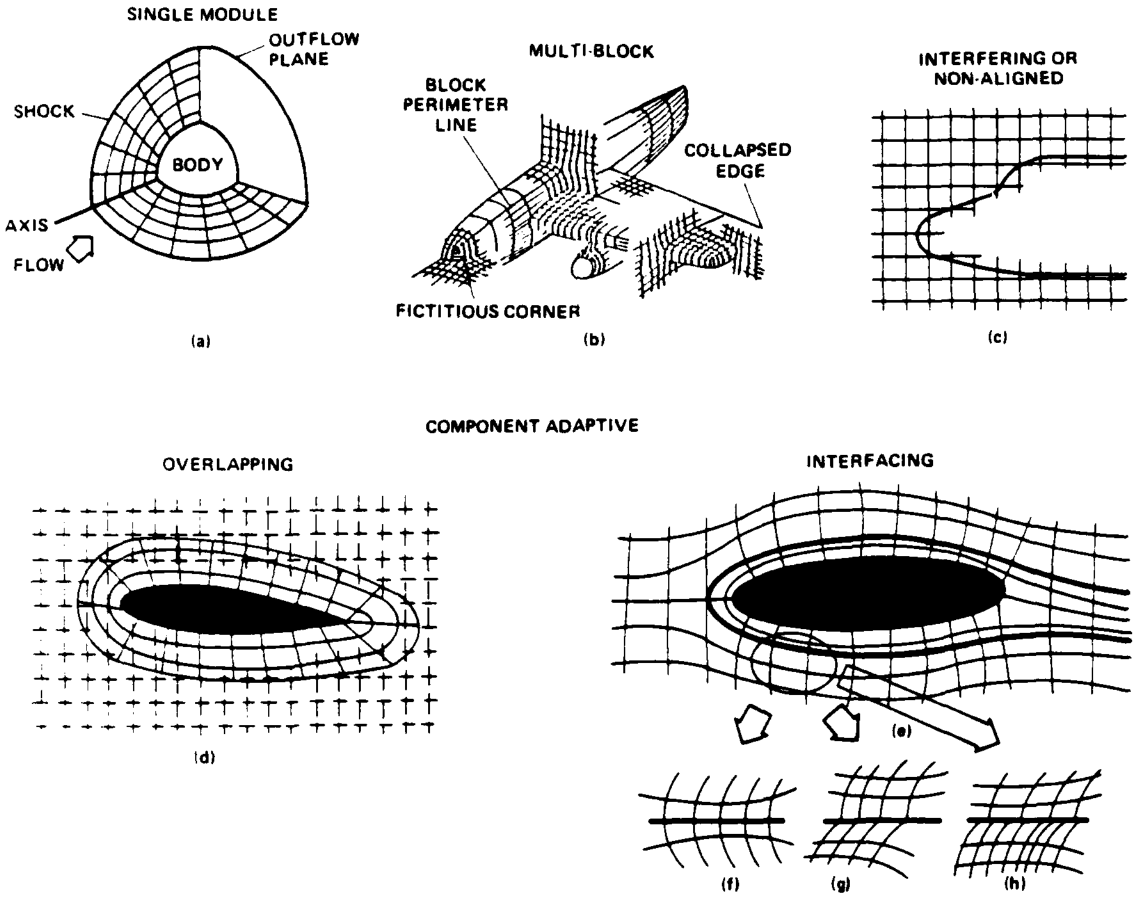


Fig. 20. Grid generation concepts (Ref. 5).

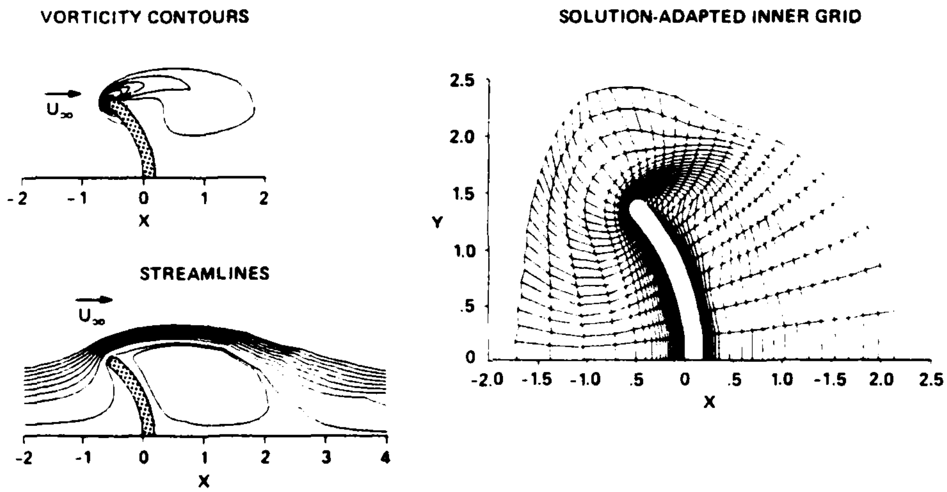


Fig. 21. Solution-adaptive grid for Navier-Stokes calculations of the flow past a parachute (Ref. 41).

As shown in Table 2 and Fig. 18, enormous computer resources are required to solve time-dependent problems with finite-difference simulations of the Reynolds-averaged Navier-Stokes equations. Even the solutions that have been published for steady flows have used grids whose fine spacing is limited to the single direction nearly normal to the body, and hence fall within the spirit of the thin-layer approximation. This resulting computational process qualitatively simulates separated flows and flows with large-scale unsteady behaviors, but the accuracy of such simulations is still controversial.

The recent survey papers on turbulence modeling for computational aerodynamics by Marvin (Ref. 42) and Lomax and Mehta (Ref. 43) and the Proceedings of the 1980-81 AFOSR-HTTM-Stanford Conference on Complex Turbulent Flows (Ref. 44) indicate the current state of the art in this area, as well as what will be

required in the future. Since no universal model exists, most researchers are now focusing their attention on creating a catalog of models based on fundamental building block experiments, and most of these models are being carefully tested computationally to determine their capabilities and limitations.

An overview of turbulence models, ranging from essentially no modeling at all to the hypothetical full simulation of turbulence, is given in Table 5. For unsteady flows of interest to aeroelasticians, only the viscous-wedge representation of shock-wave boundary-layer interaction, integral boundary layer (velocity-profile modeling), and zero-equation eddy-viscosity models have been used up to now. In the larger domain of steady flows, the primary research attention has turned to multiple-equation eddy-viscosity and

TABLE 5. TURBULENCE MODELS

Model	Physical Generality	Numerical Compatibility	Remarks
Viscous wedge	Very low	Very high	Shock-B.L. interaction
Integral B.L.	Low	High	Very good when highly tuned
Eddy viscosity			
Zero eqn	Low	High	Needs more tuning
.			
.			
.			
2-eqn	Medium	Low to high	$\Delta W_{GT} \approx 20\%$, $\Delta\tau$ = ?
Reynolds stress equations	High	Low	3-D separation?
Large eddy	Very high	Low (?)	Guidelines for above
Complete simulation	Complete	nth generation supercomputers	

Reynolds-stress-equation models. Today, both experiments and specialized large-eddy simulation calculations (Ref. (45)) provide guidance. However, the current calculations of practical flows use turbulence models that are "tuned" in conjunction with the numerical procedure for a specific class of flow problems. As a result, validations by means of experimental comparisons are mandatory, and confidence in the absolute values of the numerical predictions remains low.

In principle, the more general models should cover a wider range of flows with less "tuning," but users of the large aerodynamics codes may not always feel that "bigger is better." Nevertheless, it would seem that many of the nonlinear aeroelasticity problems will involve some degree of flow separation, and in three dimensions. In such cases, the two-equation eddy-viscosity models may turn out to be the best compromise between simplicity and generality. Some of the models in this category lead to stiff equations, and this raises again the problem of restrictive values of $\Delta\tau$. However, progress is being made to overcome this limitation (Ref. 46).

From this brief overview, it is clear that turbulence modeling will remain a primary pacing item in computational aerodynamics over the next decade, for both steady and unsteady applications.

3.2.4 Vortical flow modeling

Whereas the treatment of shock waves in transonic flow was a major focal point for computational aerodynamics in the 1970s, compressible flow fields with embedded regions of concentrated vorticity will probably gain prominence in the coming decade. Figure 22 illustrates some typical cases where vortices interact with components of the vehicle. Such nonuniformities in the flow can be expected to alter the steady and unsteady loading and, hence, to have aeroelastic consequences.

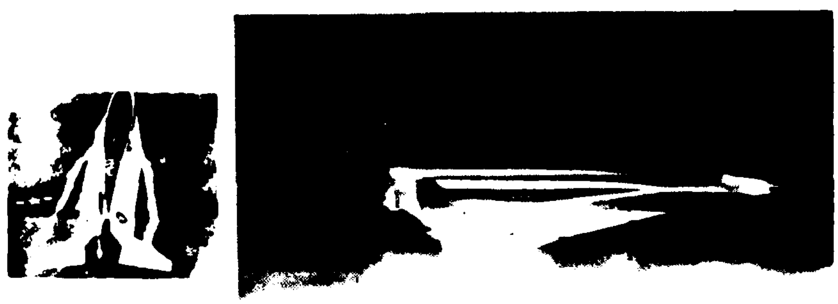


Fig. 22. Vortex interactions.

Vortices shed from sharp leading edges have been computed by a variety of methods; representative examples can be found in the Proceedings of the recent AGARD Symposium on Aerodynamics of Vortical Type Flows in Three Dimensions (Ref. 47). Within the context of the present emphasis on finite-difference CFD methods, the direct approach (e.g., Rizzi and Eriksson (Ref. 48) and Krause et al. (Ref. 49)) may be thought of as vortex capturing. That is, this approach is analogous in some sense to the more common shock-capturing methods that are used in many computational aerodynamics codes. As in shock capturing, the details of the actual phenomenon are smeared over several grid points; thus, the solution in that region is artificially grid-dependent and susceptible to the effects of numerical dissipation. In the case of concentrated tip vortices, for example, the numerical dissipation may destroy the core structure and its large gradients faster than would physical dissipation (Ref. 50).

Two alternate methods for modeling vortex flows are shown in Fig. 23. By analogy with shock fitting in transonic flows, these may be thought of as vortex fitting. The upper part of the figure portrays the method of Caradonna et al. (Ref. 51), which permits concentrated vortices to be introduced into potential-flow formulations. The prescribed vortex method shown in the lower half of the figure is due to Steinhoff (Ref. 52), and it has also been used successfully by Srinivasan and McCroskey (Ref. 53) for potential, Euler, and thin-layer Navier-Stokes analyses of unsteady airfoil-vortex interactions. In these applications, the structure of the vortex is prescribed, but its path in space develops as part of the solution.

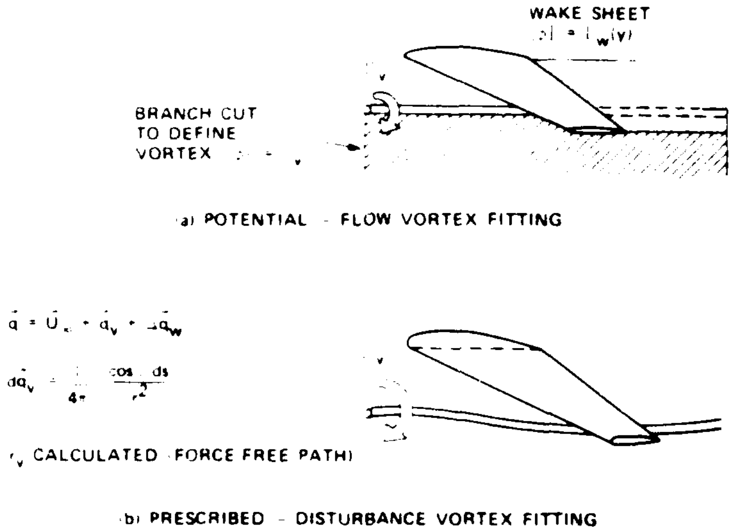


Fig. 23. Alternate methods of modeling vortex flows.

Linear panel methods (e.g., Maskew (Ref. 54)) and vortex-filament methods (e.g., Rehbach (Ref. 55) and Leonard (Ref. 56)) have been used to treat vortex-dominated flows. However, these techniques have not been applied to compressible flows up to now. The combination of shock waves and regions of concentrated vorticity represents a challenging but fruitful area of research over the next few years.

3.2.5 Aerodynamic/structural coupling

It is sometimes difficult for computational aerodynamicists to realize that their impressive results are merely the forcing functions for complex dynamic systems, and that aeroelastic analyses are often dominated by structural considerations and calculation methods that are quite alien to the world of CFD. And as we have noted previously, few specialists are highly skilled both in computational aerodynamics and structural dynamics.

The traditional method of predicting flutter boundaries has been to determine, first, the unsteady airloads via aerodynamic influence coefficients. These could be computed from linear theory as functions of the geometry of the wing, the Mach number, the reduced frequency, and the simple, uncoupled motion of the wing. This relatively simple approach can still be used in the transonic regime, if the aerodynamics can be considered as "time linearized," and relatively modest computing power is required.

If the unsteady components of the airloads depend nonlinearly on the structural motion, then some sort of direct coupling is required and time-accurate calculations must be performed, as indicated in Fig. 24. In this case, the computer-resource requirements rise sharply. Two-dimensional calculations of this type, in which the structural equations of motion and the transonic small-disturbance equations were integrated simultaneously, have been reported by Guruswamy and Yang (Ref. 57), for example.

If the series or sequential coupling technique of Fig. 24 is used, several iteration cycles for each flight condition may be required to determine the flutter boundaries. The results can be obtained faster if vector processing or pipelining techniques are used, but the solution methodologies for the structural and aerodynamic parts can be different. On the other hand, if parallel coupling were used within each time step, the number of iterations would probably be less. However, the two parts of the program would have to be totally compatible and would have to be coded very carefully if the computer resources were to be utilized effectively.

At least for the next few years, finite-difference methods are likely to remain the primary tool for analyzing complex unsteady flow fields and finite-element methods for analyzing complex structures, and

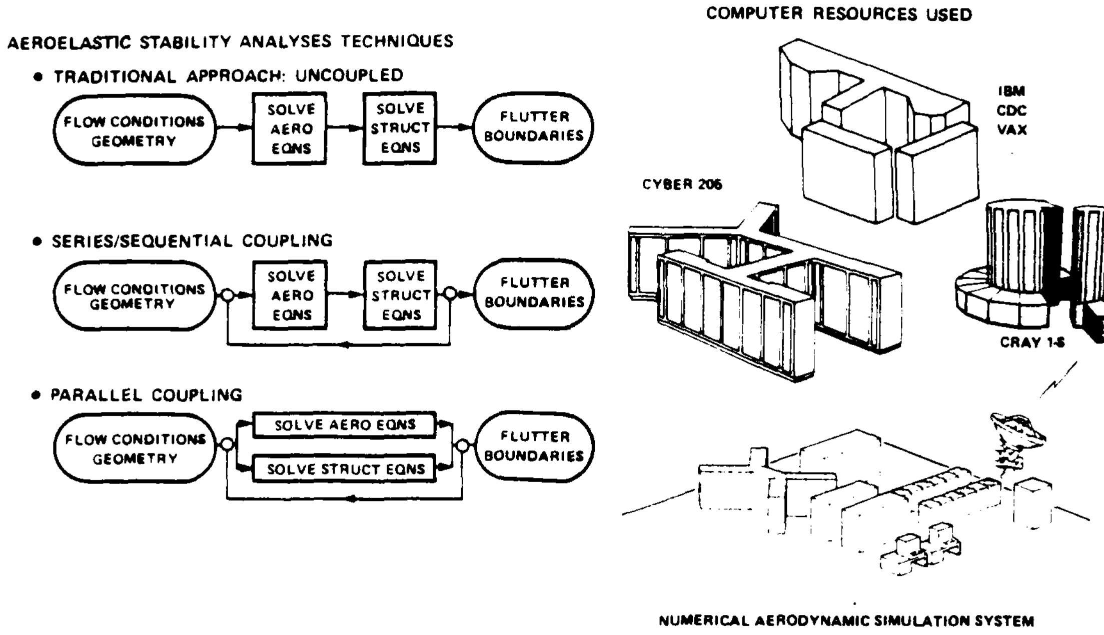


Fig. 24. Coupling of aerodynamic and structural-dynamic analyses.

the compatibility of these two approaches may be a problem. A possible strategy that would allow both computational aerodynamicists and structural dynamicists to concentrate more in their own specialties is shown in Fig. 25. This approach would use multiprocessor supercomputers; one processor solves the aerodynamic equations by whatever method is the most efficient and appropriate, while the other processor is working on the structural equations, and they would (perhaps) share the large, common memory of the central computer facility. In any case, the general issue of efficiently coupling the aerodynamic and structural parts of the flutter problem will remain a major challenge for the foreseeable future.

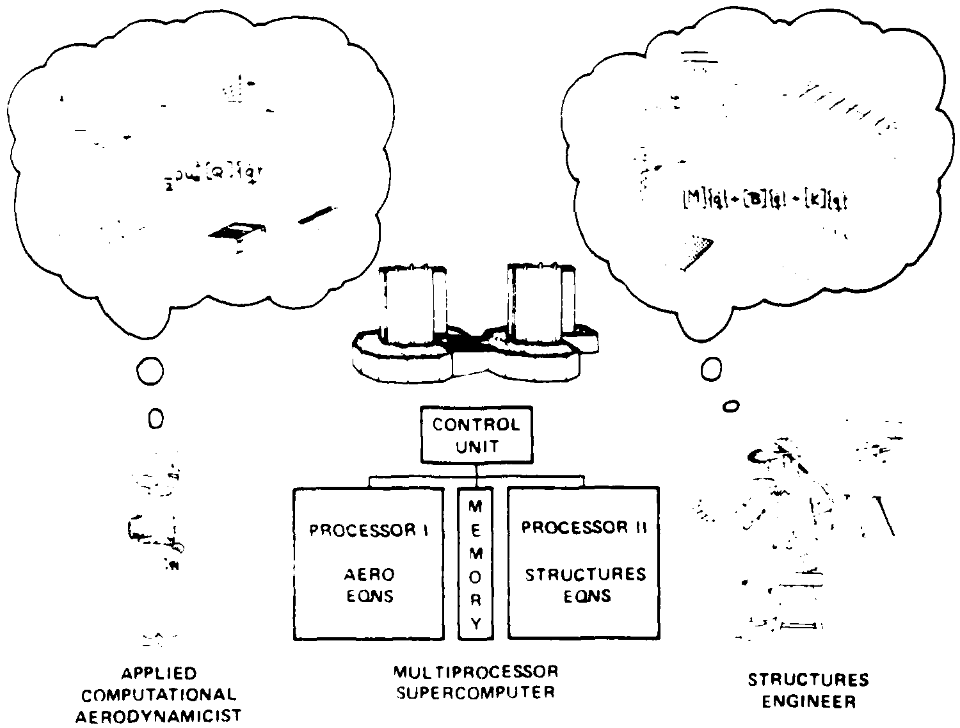


Fig. 25. Aerodynamic-structural coupling using multiprocessor supercomputers.

3.2.6 Display and pre- and post-processing of data

Simply defining the geometry of a complex aircraft configuration can be a formidable task, as attested to by a recent symposium on this subject (Ref. 58). In addition, the solution of three-dimensional

aeroelastic problems involves the management of enormous amounts of data, especially output data. This can significantly affect the productivity of the analyst who has to consume that data, make decisions about it, and formulate new avenues of approach. Therefore, the need to digest efficiently this quantity of data makes the development of optimal pre- and post-data processing procedures absolutely essential. Pre-, intermediate-, and post-processing of bulk data can only be done effectively using high-resolution, high-throughput computer graphics devices. Thus, the efficient use of on-site supercomputers will necessitate networking them with peripheral minicomputers which are linked with sophisticated interactive graphics work stations, as indicated in Fig. 26.

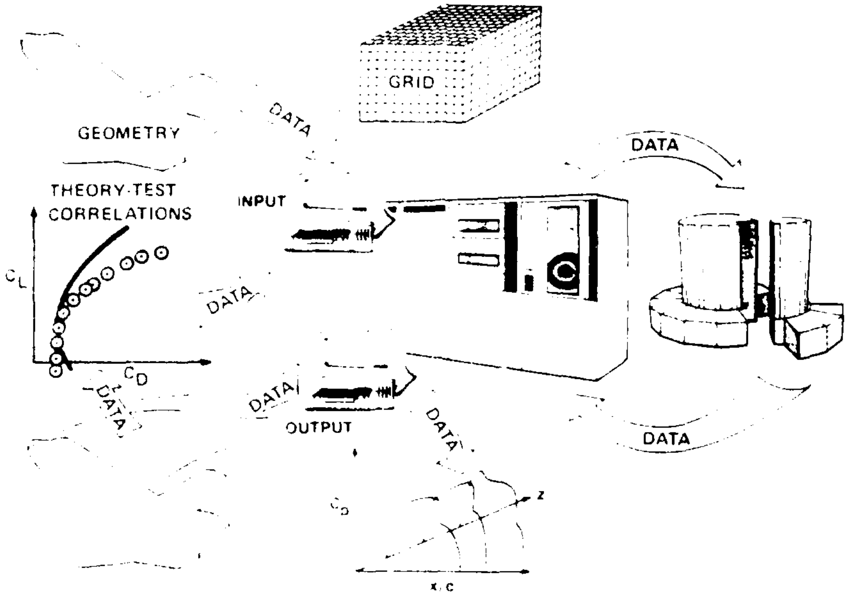


Fig. 26. Data processing and analysis.

Generation of three-dimensional, time-varying data poses yet another significant problem for the aeroelastician; namely, how to display the data meaningfully for optimum understanding and analysis. Modern graphics displays are improving at a rapid pace, and two- and three-dimensional, computer-generated color photographs can be used to great advantage (Refs. 59 and 60). Figure 27 is representative of current capabilities. The wind tunnel model (Fig. 27a) is first represented by the wire frame with hidden lines removed (Fig. 27b). However, the shaded panel, faceted surface representation (Fig. 27c) is much more valuable in visualizing the model and in spotting errors in the surface representation. Finally, the color-shading representation of the computed pressure distribution on the surface (Fig. 27d) is an important aid in examining the solution.

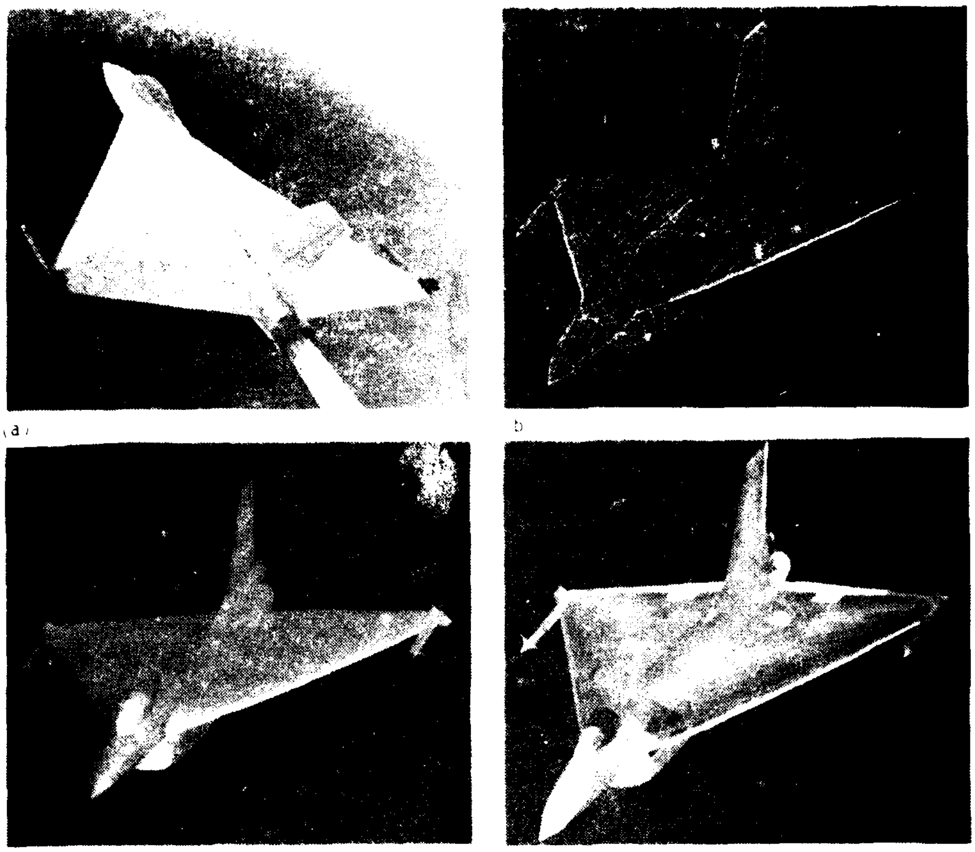
Graphical display devices and supporting software are now available to generate three-dimensional color movies, in both film and video. These can be invaluable for visualizing an evolving sequence of aerodynamic events, such as flutter, and for effectively presenting and describing these events to the technical community.

In addition, machines are also available for instantaneously producing hardcopy directly from the graphics device for a single color copy or for instant viewing of a color movie from video disk or tape. However, the production of such color movies is expensive. Although full color, three-dimensional hidden line movies will require significant computer time, it may be insignificant when compared to the computer time required to generate the data from which the movie is made. Furthermore, the benefits to be gained from such a movie justify its production cost.

3.2.7 Artificial intelligence, knowledge-based expert systems

In the preceding sections, we have discussed the computer hardware and software, the complex algorithms, the grids, the physical modeling, the aerodynamic-structural coupling, and the data processing that will be involved in aeroelastic simulations in the future. In short, these simulations will require vast expertise and enormous resources in terms of both human analysts and computer capacity. The aeroelastician will need highly developed skills in the disciplines of numerical analysis, aerodynamics, structural dynamics, computer science, and time management. To this end, some of the concepts of artificial intelligence (AI) can be applied, especially the concept of expert systems technology, as suggested in Refs. 61 and 62.

Expert systems are knowledge-based computer programs that can perform specialized tasks at, or perhaps beyond, the level of a human expert. This high level of performance is a result of "domain-specific" knowledge and strategies; expert systems are not generalists. Expert systems are distinguished from other artificial intelligence programs, and computer programs in general, by their ability to reason about their own processes of inference, and to furnish explanations regarding those processes. These distinguishing characteristics are made possible by the underlying architecture common to most expert systems. As indicated in Fig. 28, the two major components are a knowledge base, which consists of domain-dependent facts, rules, and heuristics, and a separate inference procedure that allows the system to proceed efficiently



(a) (b) (c) (d)

Fig. 27. Computer graphics representation of an aircraft and the surface pressure field. (a) Wind tunnel model, (b) wire frame [illegible] model, (c) shaded panel, (d) surface pressure distribution.

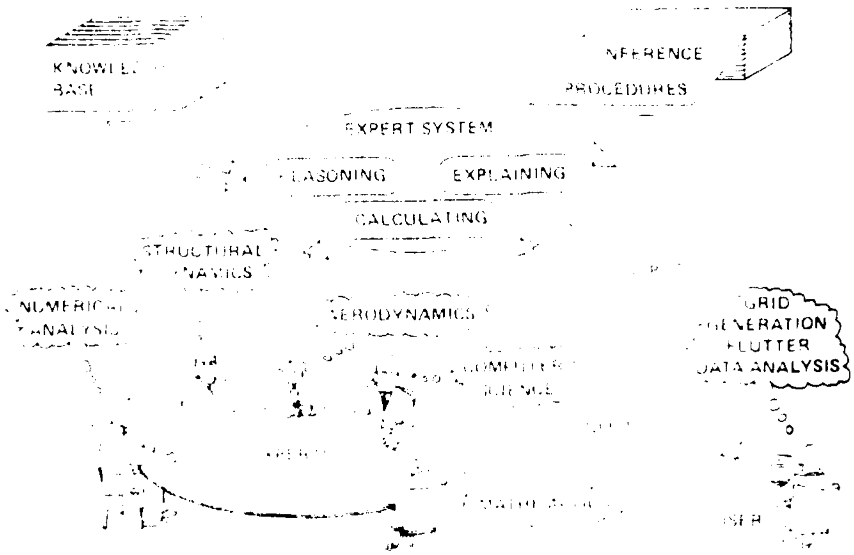


Fig. 28. [illegible] aeroelasticity.

through a maze [illegible] components are usually included [illegible]

Expert systems [illegible] The first includes the problems in which [illegible] explosion of computations, second [illegible] In addition, application of expert systems [illegible] choices, the

matters that set experts apart from beginners, are symbolic, inferential, and rooted in experiential knowledge" (Ref. 63). As indicated in Fig. 28, three-dimensional grid generation, nonlinear flutter analysis, and data processing are three areas that seem quite compatible with these characteristics.

The knowledge base for such applications would consist of facts (such as flow solvers, structures solvers, turbulence models, vortex models, and grid-generation schemes) and heuristics (i.e., experience and good judgment concerning flutter characteristics of aircraft). The inference procedures, which cannot be defined precisely at this point, would process the information that is calculated by the various stages of the program and would make decisions and draw conclusions based on the successive accumulation of new facts, starting with previous solutions. An important feature of the expert system is its ability to process information from many "outside" experts, as indicated in Fig. 28.

It must be emphasized that constructing an expert system requires a substantial investment of time and manpower. Estimates vary anywhere from less than a year for simple systems in a friendly environment with existing tools, to 15 years for complex systems in demanding environments where fundamental research and development is required. Furthermore, the level of performance of various systems varies greatly. Some of the systems that already have been built now routinely solve practical problems, while others have never made it beyond the research stage. A necessary, but not sufficient, condition for success seems to be that experienced researchers and mature technologies must be used for building almost any expert system. In any case, the potential payoff from the use of expert systems in the numerical aeroelastic simulation process is worthy of attention, and it warrants the allocation of resources as an investment in the future.

4. SUMMARY AND CONCLUSIONS

Computational aerodynamics is now a well-established tool that is used throughout the world in the design and analysis of modern flight vehicles. The past decade has seen impressive growth in the capabilities for predicting static performance and airloads over a wide range of conditions, as evidenced in the examples given in Section 2. Furthermore, this growth seems to be sustaining itself, both in terms of computer speed and memory and in the numerical methods. Except for the limitations of turbulence modeling, the showcase problems of 1974 can be solved routinely today. Progress in the more specialized areas of unsteady aerodynamics and flutter analysis has tended to lag the developments in steady aerodynamics; but the pace is quickening, and the potential for further improvements now seems to be even greater.

The primary factors that limit computational aerodynamics in its applications to aeroelastic analyses are the costs of performing a large number of nonlinear calculations, and the validity of the numerical simulations. The validity is essentially determined by the turbulence modeling, by the ability of the grid to resolve the relevant details of the flow field, and by the accuracy of the finite-difference solutions in representing the physical flow. The cost of the calculations is determined by the computer hardware and software; by the manpower required to implement the codes and to digest the results; and, in typical unsteady calculations, by the stability restrictions on the time step that can be used for the more sophisticated methods of analysis.

Fortunately, the trends are highly favorable for most of these limiting factors. The area of turbulence modeling is probably the one with the least optimism, although the manpower limitations are of concern. The analysis in Section 3 indicates that a complete, and perhaps quantitative, simulation of the transonic viscous flow over complex configurations will become possible within the next decade. This goal will be achieved, however, only with the aid of high-quality physical experiments. That is, detailed experiments will have to play crucial roles in improving the turbulence and vortex modeling and in guiding and validating the numerical simulations, whatever their levels of complexity.

However, the cost to calculate hundreds of combinations of flow parameters, structural frequencies and mode shapes, and wing-store configurations will be high enough so that aeroelasticians will continue to want more approximate "engineering" methods. The development of better, and less costly, more approximate techniques will be greatly enhanced by an intelligent combination of the large-scale numerical simulations and wind-tunnel experiments. Finally, the expert-system concept of artificial intelligence could possibly hasten the achievement of the aeroelasticians' goals.

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16. Abstract

Applications of computational aerodynamics to aeronautical research, design, and analysis have increased rapidly over the past decade, and these applications offer significant benefits to aeroelasticians. This paper traces the past developments by means of a number of specific examples, and projects the trends over the next several years. The crucial factors that limit the present capabilities for unsteady analyses are identified; they include computer speed and memory, algorithm and solution methods, grid generation, turbulence modeling, vortex modeling, data processing, and coupling of the aerodynamic and structural dynamic analyses. The prospects for overcoming these limitations are presented, and many improvements appear to be readily attainable. If so, a complete and reliable numerical simulation of the unsteady, transonic viscous flow around a realistic fighter aircraft configuration could become possible within the next decade. The possibilities of using artificial intelligence concepts to hasten the achievement of this goal are also discussed.

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